

# IMPACT BENDING FATIGUE OF WOOD<sup>1</sup>

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## ABSTRACT

Repeated impact tests were conducted using a four-point bending method on an impact machine of the dropping type to obtain fundamental information on the impact bending fatigue of a wood board with a circular hole at the center of its width. Test material used was Red Lauan (*Shorea negrosensis* Foxw.).

Strain distribution along the specimen length due to repeated impact blows is affected by the radius of the hole ( $r$ ). In the case of the 15-mm-radius specimen, the strain distribution is opposite that of the control specimen (specimen without a hole). Fracture was classified into two types according to  $r$ . The relation between the impact fracture load ( $P_f$ ) and the number of impact blows to fracture ( $N$ ) is expressed by  $P_f = a \cdot N^{-m}$  ( $a, m$ : constant). Fatigue of the 5-, 10-, 15-mm-radius specimen is faster than that of the 2-mm-radius or control specimen. Among the former specimens, the fatigue becomes larger with decrease in  $r$ . The notch sensitivity is 0.12–0.32 in the case of the 5-, 10-, 15-mm-radius specimen and only 0.004 in the case of the 2-mm-radius one in the impact bending fatigue test. The ratio of the impact fracture load to that of the control specimen decreases with  $r$  and  $N$  except for the case of the 2-mm-radius specimen.

**Keywords:** Impact bending, fatigue, defect size, *Shorea negrosensis* Foxw.

## INTRODUCTION

In many cases where wood and wood-based materials are used in construction, the reduction in strength due to repeated impact loading must be considered. This is especially necessary when the materials have a notch or hole in them, because the fatigue and permanent strain growth will advance rapidly at the position of the notch or hole.

However, there is little literature dealing with the impact fatigue properties of wood and wood-based materials with a notch or hole (Kollman and Côté 1968; Ylinen 1944; Krech 1960). Therefore the author has studied the fatigue behaviors of these materials by repeated impact tensile and bending load tests (Miyakawa and Mori 1976, 1977, 1980), and in the previous report (1981) the impact bending fatigue of wooden beams with a semi-circular notch at the tensile side was examined and the effect of the notch radius on the fatigue strength of the materials was then discussed.

Consequently, the present study aims to obtain fundamental information on the impact bending fatigue of a wood board containing a circular hole at the center of its width. These results will provide useful data for practical applications such as flooring board, table top (top boards of furniture), and wooden pallets.

In the experiment, impact blows were applied repeatedly on a bending specimen

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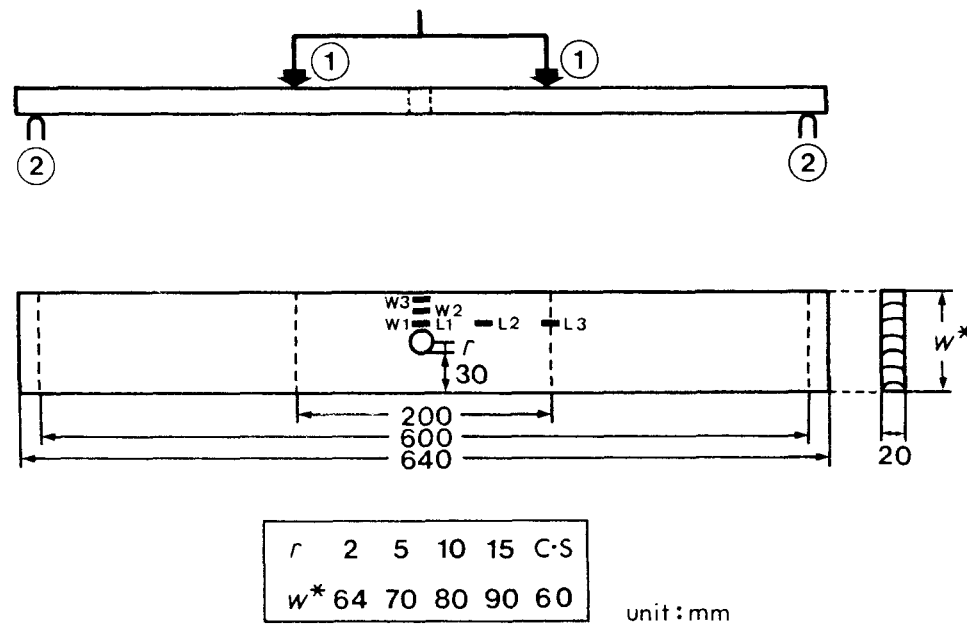


FIG. 1. View of the specimen and testing condition. ①: loading portion, ②: fulcrum, W1-W3 and L1-L3: gauge number in the direction of width and length of the specimen,  $r$ : radius of hole, C·S: control specimen,  $W^*$ : total width.

by use of an impact machine of the dropping type. The main items measured were: strain distributions in the direction of width and length on the tensile surface of the specimen, the type of specimen fracture, the relationship between impact energy and the number of impact blows to fracture ( $N$ ), and also the relation impact fracture load and  $N$ ; furthermore the notch sensitivity (ratio of the strength reduction to the stress concentration) can be calculated from the stress concentration factor and the strength reduction factor.

#### EXPERIMENTAL

##### *Test material and specimen*

Test material used was straight-grained Red Lauan (*Shorea negrosensis* Foxw.), with an air-dry specific gravity of 0.52, and a moisture content of 15.5%.

All test specimens were 20 mm thick (tangential direction) and 640 mm long (direction parallel to grain). The specimens were 60, 64, 70, 80, or 90 mm wide (radial direction) with circular holes of 0, 2, 5, 10, or 15 mm radius, respectively, positioned at the center of the length of the board as shown in Fig. 1. The specimens of 60 mm width were control specimens. Therefore, the size of the specimen with holes was equal to the control specimen except that the total width was larger by its hole diameter than that of the control specimen. The specimens of thirty pieces were prepared for one type, and the total was 150 pieces.

##### *Apparatus for bending test*

Repeated impact tests (impact fatigue tests) were performed by a four-point bending method on an impact machine of the dropping type. This machine con-

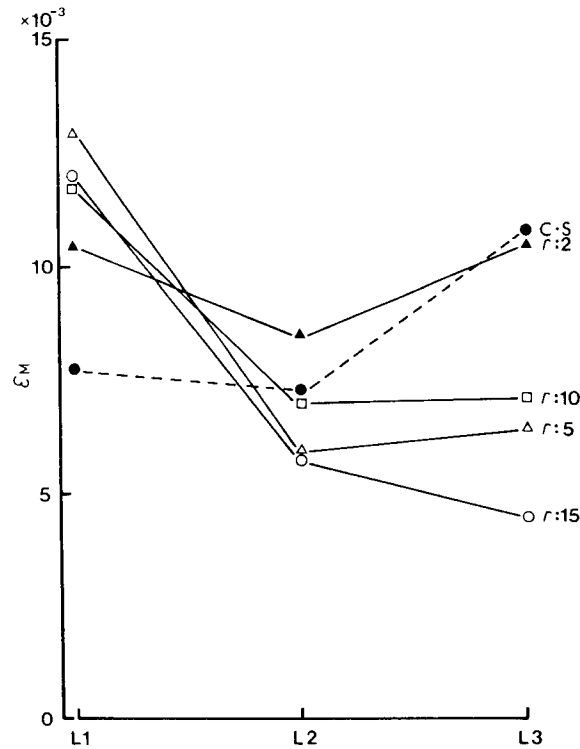


FIG. 2. Final strain distribution in the direction of length on the tensile surface in static test. L1–L3,  $r$ , C:S: refer to Fig 1.  $\epsilon_M$ : maximum strain in static test.

sisted of: a dropping hammer equipped with a device to eliminate rebound (weight of hammer = 10.3 kg; radius of crossheads = 15 mm), an iron foundation and fulcrums to support the specimen, guide supports for fitting the scale and indicator, and equipment to control an electromagnetic hook and a geared brake motor as described in the previous paper (Miyakawa and Mori 1980, 1981).

Impact loading was applied to the specimen automatically by the above machine and was continued until the specimen fractured, or until one thousand repetitions of impact blows were completed without fracture. The drop height was 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, or 800 mm, and its height was kept constant regardless of the number of repetitions (i.e., impact energy was constant). Specimens were loaded on the radial face with a load span of 200 mm as shown in Fig. 1.

For comparison, static bending tests of specimens having identical dimensions were performed using an Instron testing machine at a crosshead speed of 2 mm per minute.

#### *Measuring methods*

The acceleration of the dropping hammer when it contacted the specimen was measured by an accelerometer attached to the hammer, and the strains in the specimen resulting from the impact blow were measured by strain gauges attached to its tensile surface. Figure 1 also shows the five positions where the strain gauges

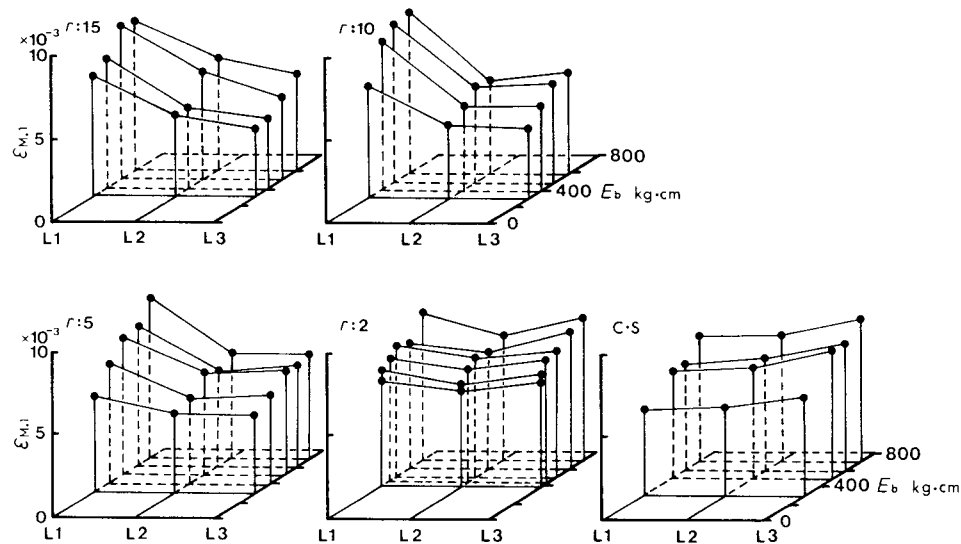


FIG. 3. Strain distributions in the direction of length on the tensile surface when the first impact blow is applied.  $\epsilon_{M,1}$ : maximum strain at the first impact blow,  $E_b$ : impact energy expressed by the product of hammer weight and dropping height. L1-L3,  $r$ , C-S: refer to Fig. 1.

were applied parallel to grain. The acceleration and strains were recorded on an electromagnetic oscillograph.

The load when the specimen has been fractured by an impact blow can be calculated using the following equation:

$$P = M \cdot A \quad (1)$$

where

- $P$  = impact fracture load
- $M$  = mass of hammer
- $A$  = acceleration.

## RESULTS

### Static bending test

The strain distribution in the width direction of specimens with holes shows a maximum value at the neighborhood of the hole (W1) and has a gently decreasing slope going away from the hole for any load.

The length-wise strain distribution at the time of specimen fracture varies with the radius of the hole in the specimen as shown in Fig. 2. In the case of the specimens with a hole of 15 mm radius, 10 mm radius, and 5 mm radius (15-mm-radius, 10-mm-radius, and 5-mm-radius specimen) there is a maximum value at the neighborhood of the hole (L1), which decreases going away from the hole. On the other hand, in the control specimen the strain value is a maximum at the load point (L3). For specimens having a 2-mm-radius hole, the strain reaches a minimum at the middle portion (L2) and a maximum at L1 and L3.

These tendencies of strain distribution in static tests have a common characteristic with those in impact tests as described later.

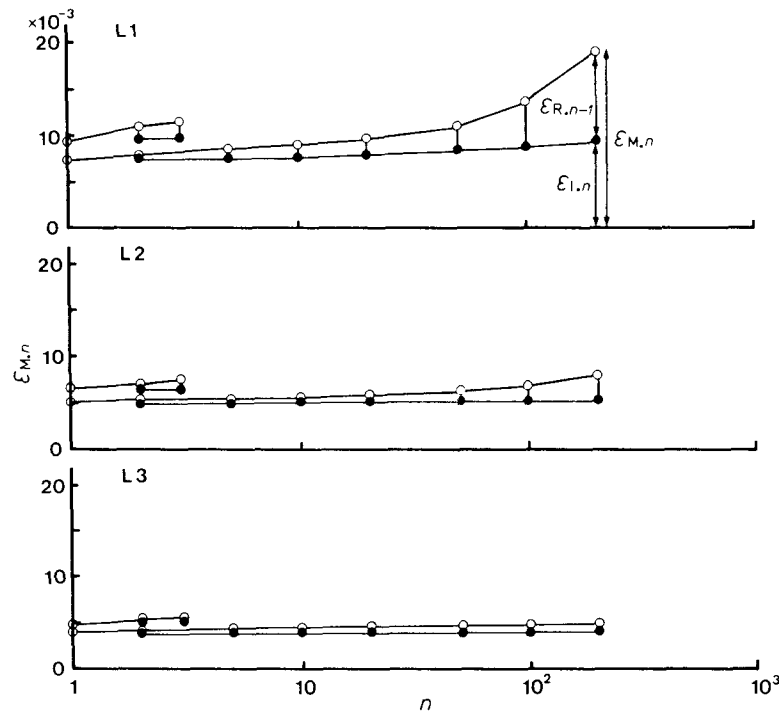


FIG. 4. Variation of total strain ( $\epsilon_{M,n}$ ), impact strain ( $\epsilon_{I,n}$ ), and residual strain ( $\epsilon_{R,n}$ ) with increase of repetition number ( $n$ ) at the portion of L1, L2, and L3 on the 15-mm-radius specimen.

The average fracture load of the ten control specimens in static test ( $P_s \cdot o$ ) was 292 kg, and that of ten specimens with a hole of 2, 5, 10, or 15 mm radius ( $P_s$ ) was 290, 283, 285, or 282 kg, respectively.

#### Impact bending fatigue test

*Strain distribution. (a) Direction of width.*—The strain value of the specimen with a hole caused by the first impact blow shows the maximum at the neighborhood of the hole and decreases with distance from the hole. This distribution varies a little with the radius of hole, but the effect of hole size is not conspicuous.

After the first impact, residual strain remains in the specimen. The total strain value is therefore represented by the sum of the impact strain and the residual strain as described in preceding reports (Miyakawa and Mori 1976, 1980). However, the final distribution of the total strain of the specimen with a hole is similar to the distribution in the case of static test. On the other hand, the strain distribution of the control specimen naturally shows equal values at the three positions for any number of impact blows, that is, the strain is constant along the width.

*(b) Direction of length.*—The strain distribution of the specimen with a hole caused by the first impact blow is shown in Fig. 3. In the case of the 15-mm-radius specimen, the strain has a maximum value at the neighborhood of the hole and decreases going away from the hole. For specimens with a smaller radius, the strain value at the neighborhood of the hole is smaller while the strain value at the load point is larger. In the case of the control specimen, the distribution is



FIG. 5. Fracture of test specimen with a hole in impact fatigue test. (a) specimen with a hole of 15 mm radius. (b) specimen with a hole of 2 mm radius.

the opposite of that of the 15-mm-radius specimen, namely, the strain value increases going away from the center. It can be seen from this figure that the strain value at each position is proportionate to the magnitude of impact energy ( $E_b$ ).

These results demonstrate that the effect of the hole sizes on the strain distribution is more evident in the direction of length than in the direction of width. The variation of strain distribution with increased impact (Fig. 4) is similar to that of the strain distribution with increased static loading.

*Fracture type.*—Figure 5 shows that the type of fracture of an impacted specimen with a hole varies with the radius of the hole. Specimens with a hole of 5, 10, or 15 mm radius correspond to a fracture through the hole diameter at the center of the bending span (Fig. 5a). Both the specimen with a hole of 2 mm radius and the control specimen fractured roughly within the load span (Fig. 5b). These types of fracture are related to the above-mentioned strain distribution at the final step of loading. Fracture occurs through the hole in the case of the 5-, 10-, 15-mm-radius specimen since the strain value of the center portion (L1) is larger than the other portions. On the other hand, in the case of the 2-mm-radius and control specimen, fracture occurs widely within the load span since the strain values of the three portions are only slightly different from each other, or increase with distance from the center.

*Impact fracture load.*—There exists a negative rectilinear correlation on a logarithmic scale between impact fracture load ( $P_1$ ) and the number of impact blows to fracture ( $N$ ). This relationship can be expressed by the following empirical equation as shown in Fig. 6:

$$P_1 = a \cdot N^{-m} \quad (2)$$

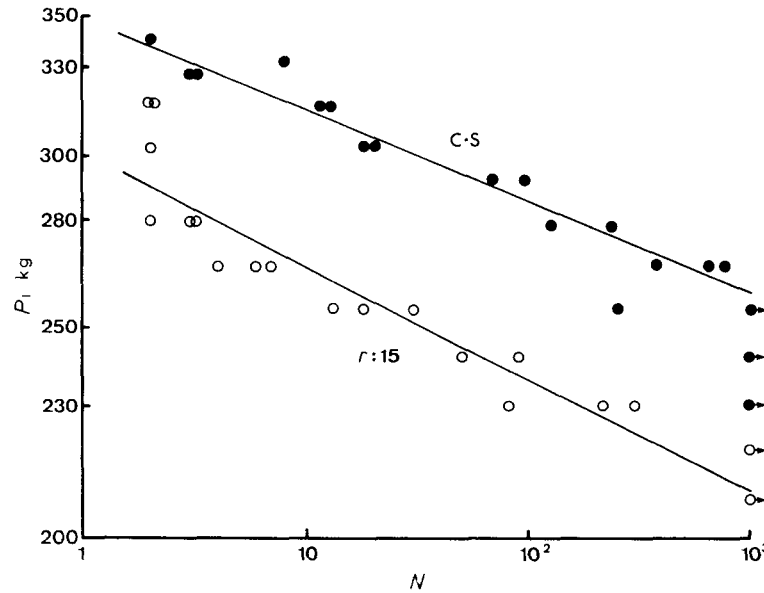


FIG. 6. Relation between impact fracture load ( $P_1$ ) and repetition number to fracture ( $N$ ). ●: control specimen, ○: specimen with a hole of 15 mm radius.

The experimental calculated values of  $a$  and  $m$  are shown in Table 1. The constant  $a$  is the fracture load when the specimen is fractured at the first impact blow. The value of the control specimen is 1.02–1.15 times as much as that of specimens with holes. The exponent  $m$  is the rate of fatigue strength reduction with number of cycles to fracture, and the value of the 5-, 10-, 15-mm-radius specimen is about 1.2–1.6 times as much as that of the 2-mm-radius and control specimen. That is, the fatigue life in the former specimens is shorter than that in the latter specimens. With the exception of the 2-mm-radius specimen, it is indicated that the smaller the hole radius, the faster the fatigue. But the 2-mm-radius specimen shows the lowest value of  $m$ . This result may be due to the fact that since the solid wood is of porous construction, a hole with a radius in the order of 2 mm will not have direct effects upon the reduction of fatigue strength in this testing condition. Figure 6 shows an example of the relationship between  $P_1$  and  $N$ . As seen in the figure,  $P_1$  decreases remarkably with  $N$  on a logarithmic scale similar to the relationship between impact energy  $E_b$  (calculated by the product of the hammer weight and the drop height) and  $N$ .

TABLE 1. Calculated values of exponent ( $m$ ), constant ( $a$ ) and coefficient of correlation ( $R$ ) in Eq. (2).

$r$	$m$	$a$	$R$
C·S	0.0437	348	0.79
2	0.0377	332	0.77
5	0.0607	341	0.91
10	0.0573	311	0.74
15	0.0536	302	0.75

$r$ : radius of hole, C·S: control specimen.

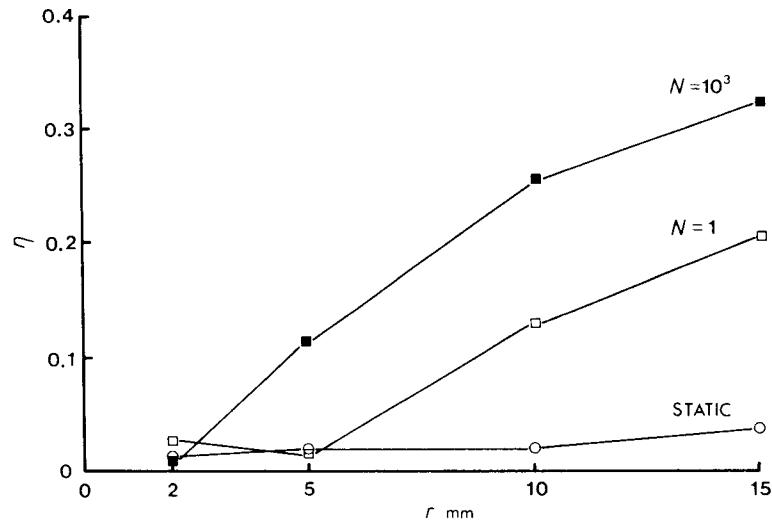


FIG. 7. Relation between notch sensitivity ( $\eta$ ) and radius of hole ( $r$ ). ○: static bending test, □: impact bending test ( $N = 1$ ), ■: impact bending test ( $N = 10^3$ ).

#### DISCUSSION

##### Notch sensitivity

The notch sensitivity ( $\eta$ ) (Moore 1945) expressed by the following Eq. (3) is obtained in order to make clear the effectiveness of the stress concentration caused by the hole on the fracture load of the specimen with a hole.

$$\eta = \frac{\beta - 1}{\alpha - 1} \quad (3)$$

$\alpha$  is the stress concentration factor (Nishida 1967) which can be calculated approximately by

$$\alpha = 1 + \frac{1}{2}(\alpha_{r/b \rightarrow 0} - 1) \left[ 1 + \left( \frac{b-r}{b} \right)^3 \right] \quad (4)$$

where

$\alpha_{r/b \rightarrow 0}$  = stress concentration factor in the case of  $r/b \cong 0$

$b$  = half of specimen width.

$r$  = radius of hole.

TABLE 2. Stress concentrated factor ( $\alpha$ ), strength reduction factor ( $\beta$ ) and notch sensitivity ( $\eta$ ) in Eq. (3).

r	$\alpha$	$\beta$			$\eta$		
		Static	Impact		Static	Impact	
			N = 1	N = 10 <sup>3</sup>		N = 1	N = 10 <sup>3</sup>
2	2.63	1.01	1.05	1.01	0.01	0.03	0.004
5	2.26	1.03	1.02	1.15	0.02	0.02	0.12
10	1.91	1.02	1.12	1.23	0.02	0.13	0.25
15	1.74	1.03	1.15	1.24	0.04	0.21	0.32

$\beta$ : ratio of fracture load of control specimen to that of specimen with a hole,  $r$ : radius of hole.



TABLE 3. Ratio of fracture load of specimen with a hole to that of control specimen in bending test.

	<i>r</i>	2	5	10	15	Mean
<i>K<sub>I</sub></i>	<i>N</i> = 1	0.95	0.97	0.89	0.86	0.92
	<i>N</i> = 10	0.97	0.94	0.87	0.85	0.91
	<i>N</i> = 10 <sup>2</sup>	0.98	0.90	0.84	0.83	0.89
	<i>N</i> = 10 <sup>3</sup>	0.99	0.87	0.81	0.80	0.87
<i>K<sub>S</sub></i>		0.99	0.97	0.98	0.97	0.97

*r*: radius of hole, *N*: repetition number to fracture, *K<sub>I</sub>* and *K<sub>S</sub>*: the values obtained in impact bending test and in static bending test by the Eq. (6).

$\beta$  means the strength reduction factor and is represented by the ratio of the fracture load of the control specimen to that of the specimen with a hole as shown in Eq. (5).

$$\beta = P_{I \cdot O} / P_I \quad (= P_{S \cdot O} / P_S) \quad (5)$$

$P_I$  and  $P_{I \cdot O}$  = impact fracture load of the specimen with a hole and the control specimen, respectively.

$P_S$  and  $P_{S \cdot O}$  = static fracture load of the specimen with a hole and the control specimen, respectively. (Annotation: when  $\eta$  is 1 ( $\alpha = \beta$ ), the stress concentration caused by the hole affects most sensitively the fracture of the specimen. On the other hand, when  $\eta$  is zero ( $\beta = 1$ ), the stress concentration is unrelated to the fracture of the specimen.)

The values of  $\alpha$  and  $\beta$  for this test are presented in Table 2, and the calculated values of  $\eta$  are shown in Fig. 7.

Figure 7 shows that even though the values of  $\eta$  for the static tests are very small and hardly affected by  $r$ , the values for the impact tests increased with  $r$  and  $N$ . However, the values of  $\eta$  obtained in this report are considerably lower than those of the specimens with a semi-circular notch as in Miyakawa and Mori (1981). And it can be said that the value of  $\eta$  of a solid wood specimen is generally lower than that of metal materials (Moore 1945; Nishida 1967).

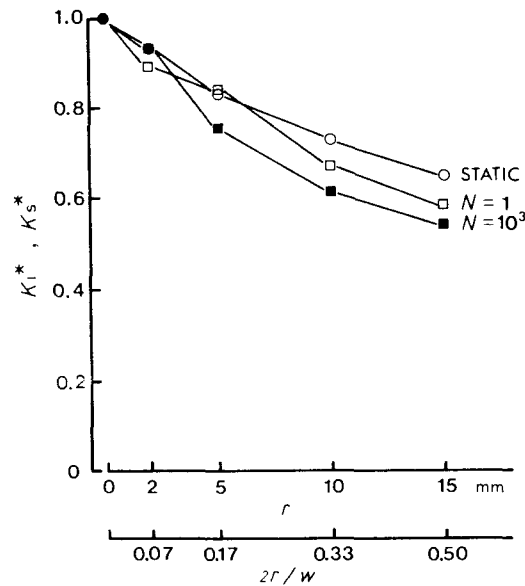
#### *Comparison of the fracture loads between specimen with a hole and control specimen*

There are two methods in computing the ratio of the fracture load of a specimen with a hole to that of a control specimen. In the first way, the ratio is estimated based on the fracture load of a control specimen whose width is equal to the minimum width of the specimen with a hole used in the tests. In the second way, the width of the control specimen is equal to the total width of the specimen with a hole. The ratio of the first method will be necessary to verify that the reduction of the fracture load of the specimen with a hole is caused by the stress concentration. The second method will be necessary in evaluating the structural board for practical use.

In the case of impact fatigue test and static test, the ratio ( $K_I$ ), and ( $K_S$ ) in the first method is expressed by the inverse of  $\beta$ ,

$$K_I = 1/\beta = P_I / P_{I \cdot O} \quad (K_S = P_S / P_{S \cdot O}) \quad (6)$$

The calculated results of  $K_I$  and  $K_S$  are presented in Table 3. In the case of the static test, the value of  $K_S$  is nearly equal to 1.00. This result indicates that the

FIG. 8. Relation of  $K_I^*$ ,  $K_S^*$  to  $2r/w$ .

stress concentration due to the hole at the center of the width of the specimen hardly affects the fracture load of the specimen with a hole. On the other hand, in the case of the impact fatigue test, the value of  $K_I$  decreases with increase in  $r$  and  $N$ , with the exception of the 2-mm-radius specimen. This indicates that the stress concentration affects the reduction of fatigue strength of the specimens with a larger hole.

The ratio in the second method is calculated as follows. In the case of impact fatigue test ( $K_I^*$ ), and static test ( $K_S^*$ ),

$$K_I^* = K_I \frac{1}{1 + 2r/w} \quad \left( K_S^* = K_S \frac{1}{1 + 2r/w} \right) \quad (7)$$

( $w = 60$  mm in width)

Results of Fig. 8 indicate that values of  $K_I^*$  and  $K_S^*$  decrease with the radius of hole. The rate of decrease is larger in the order: static load, impact load ( $N = 1$ ), and repeated impact loads ( $N = 10^3$ ). As an example, in the case of the 15-mm-radius specimen which is fractured at one thousand repetitions of impact blow, the fracture load is reduced by approximately one-half of that of the control specimen whose width is equal to the total width of the specimen with a hole.

#### CONCLUSIONS

1) Strain distribution of the impacted specimen containing a hole is affected by the radius of hole. The instantaneous total strain caused by impact was represented as the sum of the impact strain and the residual strain generated in the specimen by the previous impacts. In particular, the strain distribution in the direction of length for the 15-mm-radius specimen is the opposite of that of the control specimen.

2) The specimen with a hole radius of 5, 10, or 15 mm fractures through the

hole diameter. The 2-mm-radius specimen and the control specimen fractured roughly within the load span.

3) There exists a negative rectilinear correlation on a logarithmic scale between impact fracture load ( $P_I$ ) and the number of impact blows to fracture ( $N$ ) as expressed by  $P_I = a \cdot N^{-m}$ . The exponent  $m$ , which indicates the reduced rate of strength, increases with decreasing  $r$  except in the case of the 2-mm-radius specimen.

4) In the impact bending fatigue test, the notch sensitivity is shown as 0.12, 0.25, 0.32 in the case of the 5-, 10-, 15-mm-radius specimen and only 0.004 in the case of the 2-mm-radius one for  $N = 10^3$ .

5) The ratio of the fracture load of the specimen with a hole to that of the control specimen, and whose width is equal to the minimum width of specimen with a hole, decreases with  $r$  and  $N$  except for the case of the 2-mm-radius specimen.

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